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LEVEL II

DIELECTRIC GRATING ANTENNAS

by

S.T. PENG

JULY 18, 1979

FINAL REPORT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Three basic problems associated with dielectric grating antennas are investigated. First, the radiation characteristics in the stopband region are carefully analyzed, showing the range of blindness of the antenna in the broadside direction. Second, a new perturbation procedure for grating antennas is shown numerically to yield accurate propagation characteristics including the changes in phase as well as decay constant. Finally, the scattering of a plane wave by a dielectric grating at an arbitrary incidence angle is analyzed showing the coupling between TE and TM modes.

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I. INTRODUCTION

A exploratory study on the analysis and design of a dielectric grating for use as a millimeter wave antenna was carried out by the author[1] under the Laboratory Research Cooperative Program of U. S. Army. Due to the short time limit allowed for that research effort, however, only those aspects that were urgently needed were thoroughly investigated, and there were still other important aspects that remain to be completed. Also, during the course of the investigation, new problems of fundamental importance has been identified. Therefore, the present contract was intended to supplement that research effort so that the exploratory study can be brought to a satisfactory conclusion. In orther words, it was expected that this supplementary research effort will clear up the remaining obstacles and breaks the ground for a new phase of the research on dielectric grating antennas for mm-wave applications to build up. We report here that the three aspects of the grating antenna problem as specified in the contract have been successfully carried out and extensive numerical results illustrating important physical phenomena have been obtained. First of all, the numerical difficulties encountered in the case of resonant interaction (in the stop-band region) have been overcome and a revised computer program that we have developed during the course of this investigation can now be used for any structural and source excitation parameters. This enable us to investigate broadside radiation characteristics of dielectric grating antennas. Secondly, a new perturbation technique in the phase space has been numerically demonstrate to yield accurate results for not only the radiation (or leakage) constant but also the effective index of refraction (or the normalized phase constant). A more accurate determination of the phase constant permits a better design of an antenna feeder and also a better control of the radiation angle. Finally, a computer program that takes into account the coupling between TE and TM modes in the grating region for the general oblique incidence case has been successfully developed. We believe that such a computer program is the most general one in existence for electromagnetic boundary value problems involving dielectric gratings. The computer program will enable us to study a new and important effect of finite grating width that is anticipated for mm-wave applications. While extensive and detailed results are being prepared for publication in the literature, a breif description with typical examples for each aspect of the contract is given in what follows.

II. BROADSIDE RADIATION OF A GRATING ANTENNA

In the previous research effort,[1] the radiation characteristics of grating antennas (Fig. 1) had been determined for various materials and structural parameters pertinent to mm-wave applications. Extensive numerical results regarding the radiation rate, beam width and frequency scanning characteristics have been obtained. It was demonstrated that silicon and aluminum oxide grating antennas will indeed produce enough radiation, even under the anticipated severe constraint on the length of an antenna for mm-wave applications. During the course of that investigation, however, numerical difficulties had been encountered in the stopband region. The stopband phenomenon has been a classical subject that has attracted great attention in the literature on wave propagation in periodic structures; it is understood to be due to a resonant interaction between space harmonics. The stopband encountered here is particularly interesting, because it is in a leaky wave region and has not been analyzed for dielectric grating antennas in the literature. To explore the full potential of grating antennas, it is necessary to know the radiation characteristics in the stopband region, especially if a radiating beam is expected to scan over a large angle. As proposed, we have modified the previous formulation to account for resonance interaction, and have then developed a revised computer program to allow adequate codes that properly handle the resonant interaction of space harmonics. This task has been successfully completed; an example of practical interest is given below.

The leakage constant for a silicon grating antenna was previously calculated[1] and the result is shown in Fig. 2. In a small range of frequency in the stopband region, numerical instabilities were encountered in the previous formulation. As indicated in Fig. 2, such a frequency range covers an angle of about 15° around the broadside direction. The numerical instabilities were attributed physically to the strong interaction between the fundamental and second harmonics. A strong interaction between two waves occurs when their phase velocities are almost matched; this means mathematically that the two dispersion roots for the two interacting waves are close to each other. With such an understanding, it is easy to pinpoint the main cause of the difficulties encountered in the previous analysis of grating antenna; therefore, it is clear to us that our research effort should be directed toward: (1) resolving the dispersion roots that are close together, and (2) improving the convergence rate of an iterative scheme for locating

a root. After an extensive and careful analysis, we have found a technique that accomplishes both goals stated above; it involves removal of zeros of the dispersion relation at those roots that have already been determined. This technique has been proved to be very effective for the problem at hand and fruitful results have been obtained. For the silicon grating antenna which is considered as a structure difficult to analyze because of its relatively high dielectric constant, the effective index of reflection and the leakage constant in the stopband and its vicinity have been calculated without encountering any numerical difficulty. The results are given in Figures 3 and 4, showing the sensitive behaviors of radiation characteristics under the stopband condition. The most important conclusion we can draw from these results is that even in the direction of 1° from the broadside, a sufficiently high radiation (large $\alpha\lambda$) is still achievable and an almost broadside radiation is possible.

III. NEW APPROXIMATION TECHNIQUE FOR A GRATING OF HIGH DIELECTRIC CONSTANT

Up to the present, the exact formulation of the periodic dielectric waveguide as a rigorous boundary value problem remains the only reliable method of analysis for grating antennas with high dielectric constant materials. Expectedly, such an exact analysis is very involved and has to rely on extensive numerical results for physical interpretations. For the purpose of practical antenna design, it is desirable to have simple analytic formulas that will provide physical insight regarding the wave phenomena that take place in the antenna structure. In the past, we had developed a perturbation procedure[2,3] that yielded accurate design formulas[4] for optical periodic couplers. However, it has been shown[1] that the accuracy of the perturbation results become rather poor for a silicon grating antenna ($\epsilon_f = 12$). In Reference 1, we have developed a new approximation procedure that will yield not only the leakage constant, but also the necessary change in the phase constant, which has never been accounted for in any previous approximate analysis of periodic dielectric waveguides. In contrast, the previous perturbation procedure deals with the change in harmonic amplitude and the new perturbation procedure deals with the phase directly; they may therefore be termed the amplitude and phase perturbations, respectively. We believe that this new approximation procedure will apply to gratings of high dielectric constants as well as to those of low values, but its accuracy remains to be demonstrated. Because of its practical important, it was proposed that the new approximation procedure be used to carry out extensive numerical results, and the accuracy be checked by comparison with the exact results that we have obtained in the past.

Under this contract, we have carried out an extensive numerical analysis of radiation characteristics of grating antennas by using the new perturbation procedure. Excellent results have been obtained for many structures of different parameters. The radiation characteristics for a typical structure was shown in Figs. 5 and 6. To indicate the effectiveness of the perturbation procedure, a computation of three minutes by the exact analysis requires no more than five seconds by the perturbation method by using the same computer.

It is recalled that for the previous amplitude perturbation procedure, the effective index of refraction or the normalized phase constant was taken to be that of a uniform structure with an average dielectric constant for the periodic layer. From Fig. 6, we observe that the effective index of refraction changes

considerably due to the effect of radiation and the results of both the exact and the new perturbation procedure agree quite well. Therefore, it is particularly interesting to point out that the new perturbation procedure can yield the necessary change in the phase constant as well as the attenuation constant of the grating antenna structures under consideration.

IV. GENERAL CHARACTERISTIC SOLUTIONS OF AN UNBOUNDED GRATING ANTENNA

As stated in the proposal, it is generally understood that a grating antenna for mm-wave applications will have a narrow width, at most a few wavelengths, in contrast to the thousands of wavelengths for optical period couplers. Therefore, the most challenging problem in the analysis of such an antenna structure will be to account for the effect of the finite width on the radiation characteristics of the antenna. It is well understood that a grating antenna structure of finite width is a three-dimensional boundary value problem that supports only hybrid modes, e.e., it requires simultaneous presence of "TE" and "TM" waves in the structure. To the best knowledge of the writer, no attempt has ever been made in the literature to formulate a periodic dielectric waveguide for the general case of oblique guidance,,possibly because of its mathematical complexity and lack of practical interest in the past. For the analysis of grating antenna structures of finite width, however, a satisfactory analytical (not simply numerical) treatment of the general case becomes a necessity. The grating antenna structure has been successfully formulated in an exact fashion and without any restrictive condition.[1] The formulation is carried out in terms of both sets of TE and TM Floquet mode functions of the periodic tooth region. Each of these sets of mode functions has separately been analyzed extensively in the previous formulation for the special case of normal guidance where the TE and TM modes are decoupled. What remains to be done is the development of a computer program based on this exact formulation for the general case that will account for the effect of lateral variations of electromagnetic fields on the radiation characteristics of a grating antenna.

Since scattering of a plane wave by a periodic layer is the basis for the radiation of a grating antenna, it is essential to solve the scattering problem first. Also, the scattering problem is of fundament importance by itself. As proposed, we have successfully developed a computer program for the plane wave scattering by a periodic layer and two typical examples are given in Figs. 7 and 8, showing the coupling of power between TE and TM modes. This represents the first successful analysis of a three dimensional vector boundary value problem involving a periodic structure. The computer program developed can be said to be the most general one for the grating antenna structure and is expected to have a great impact on future research on the subject.

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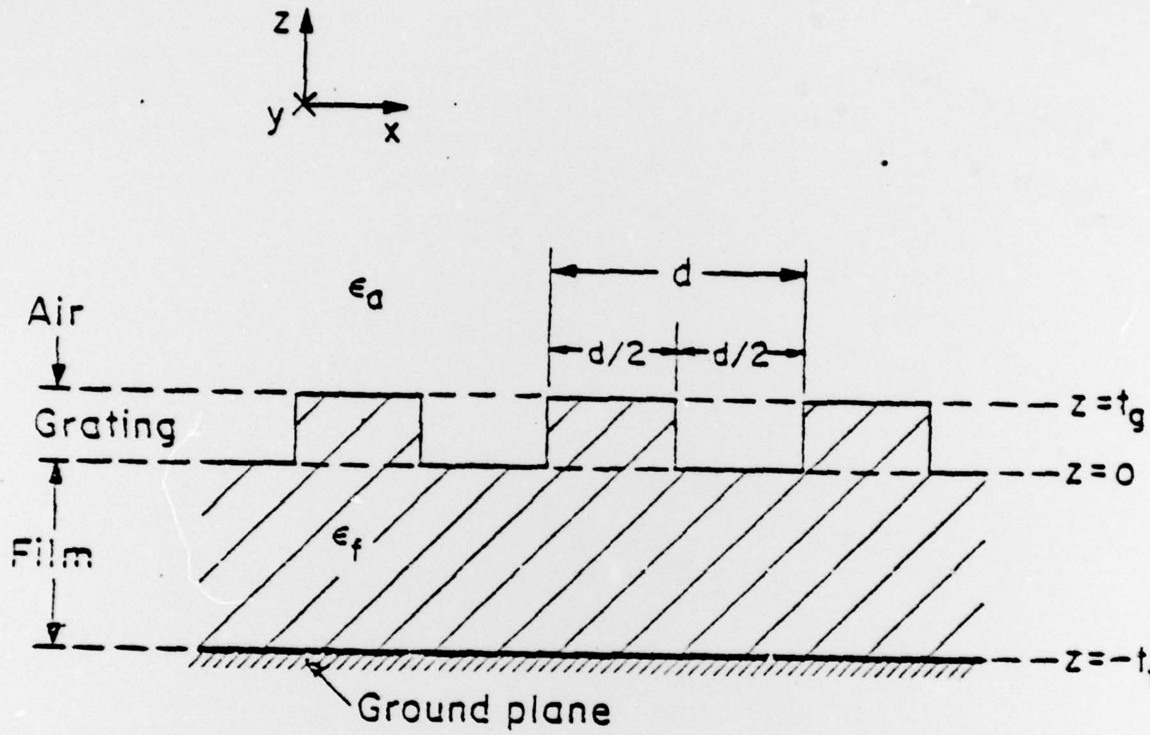

Fig. 1. Configuration of grating antenna.

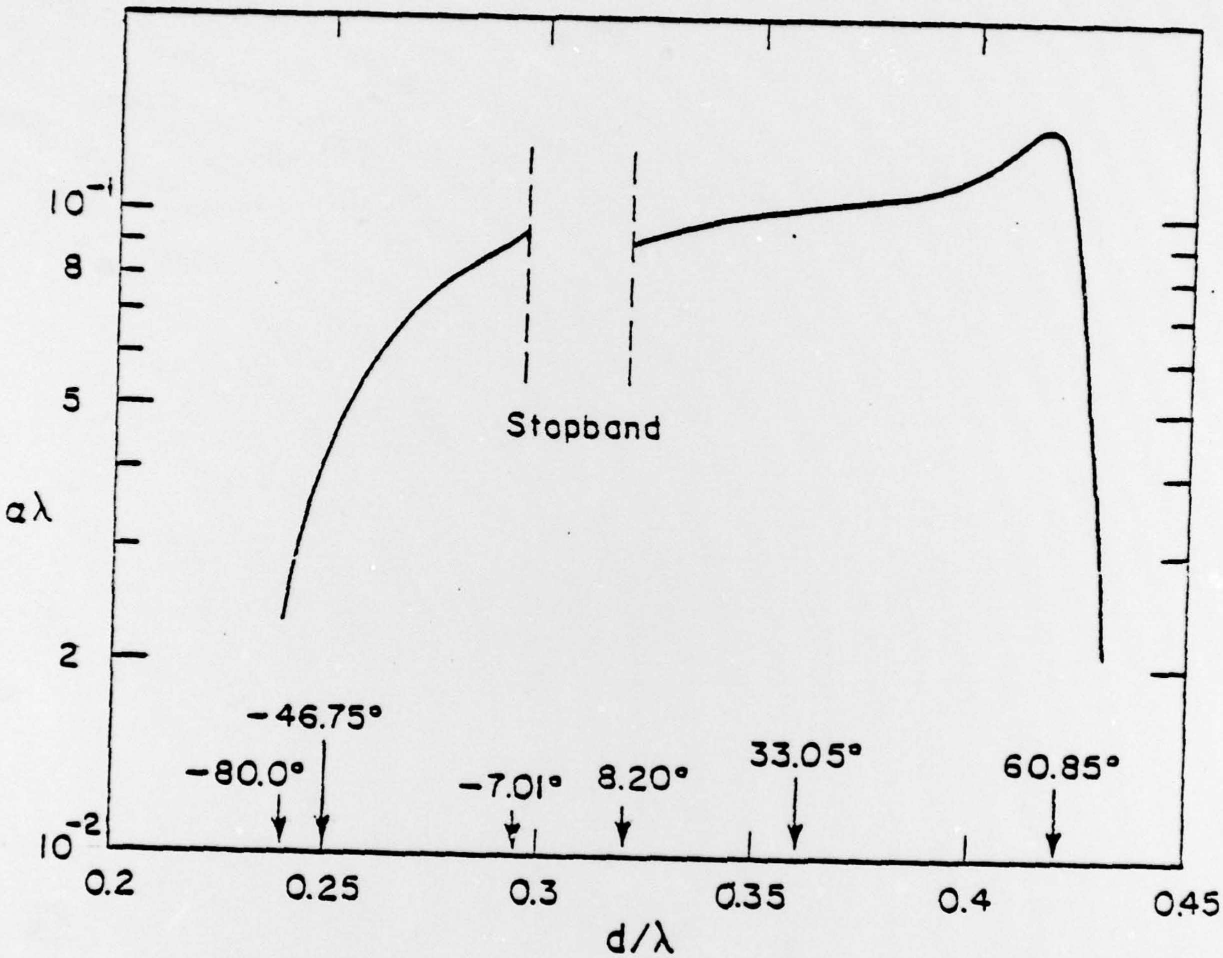

Fig. 2. Dispersion curves for silicon grating antenna - leakage constant.

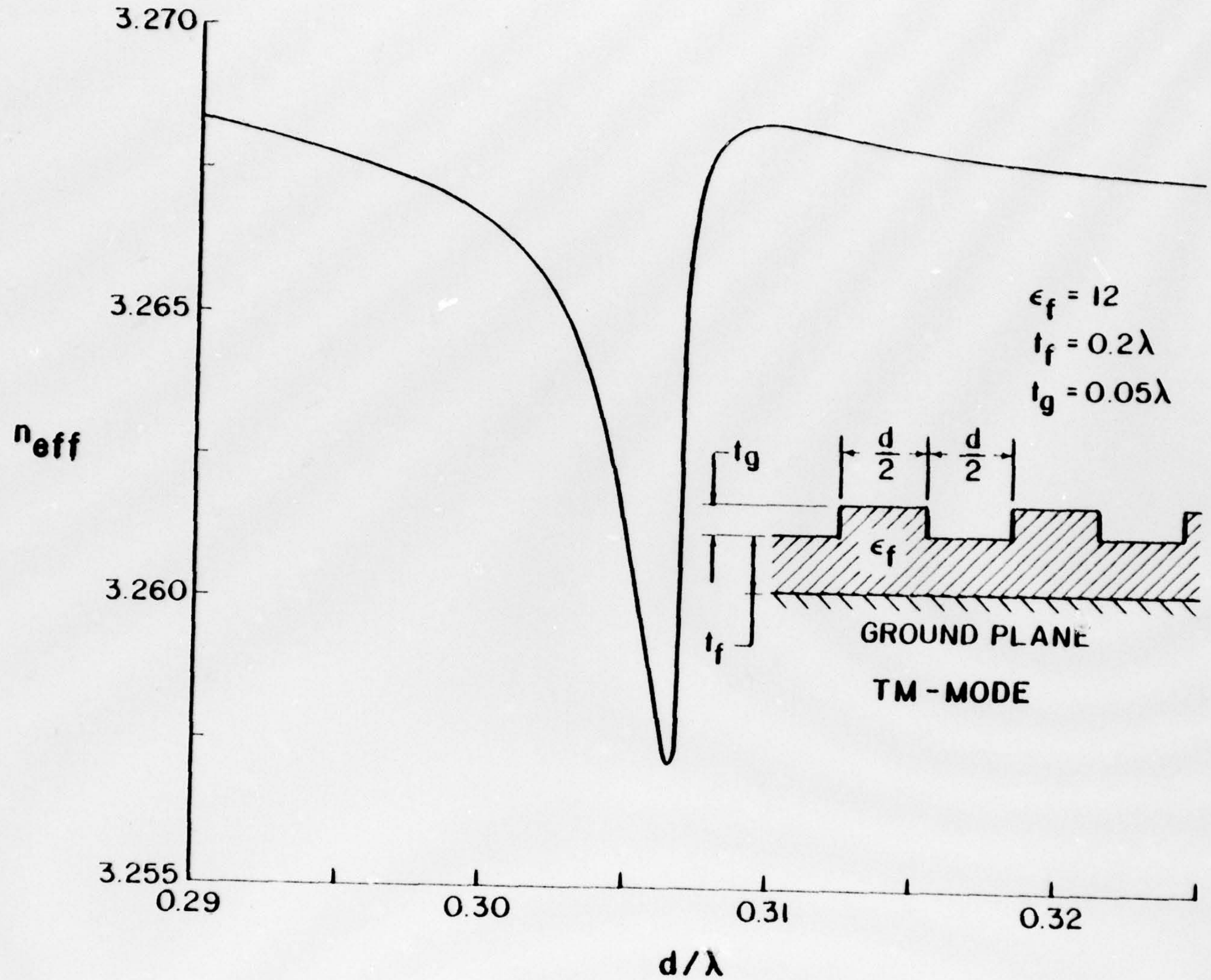

Fig. 5. Dispersion curve in the stopband region - effective index of refraction.

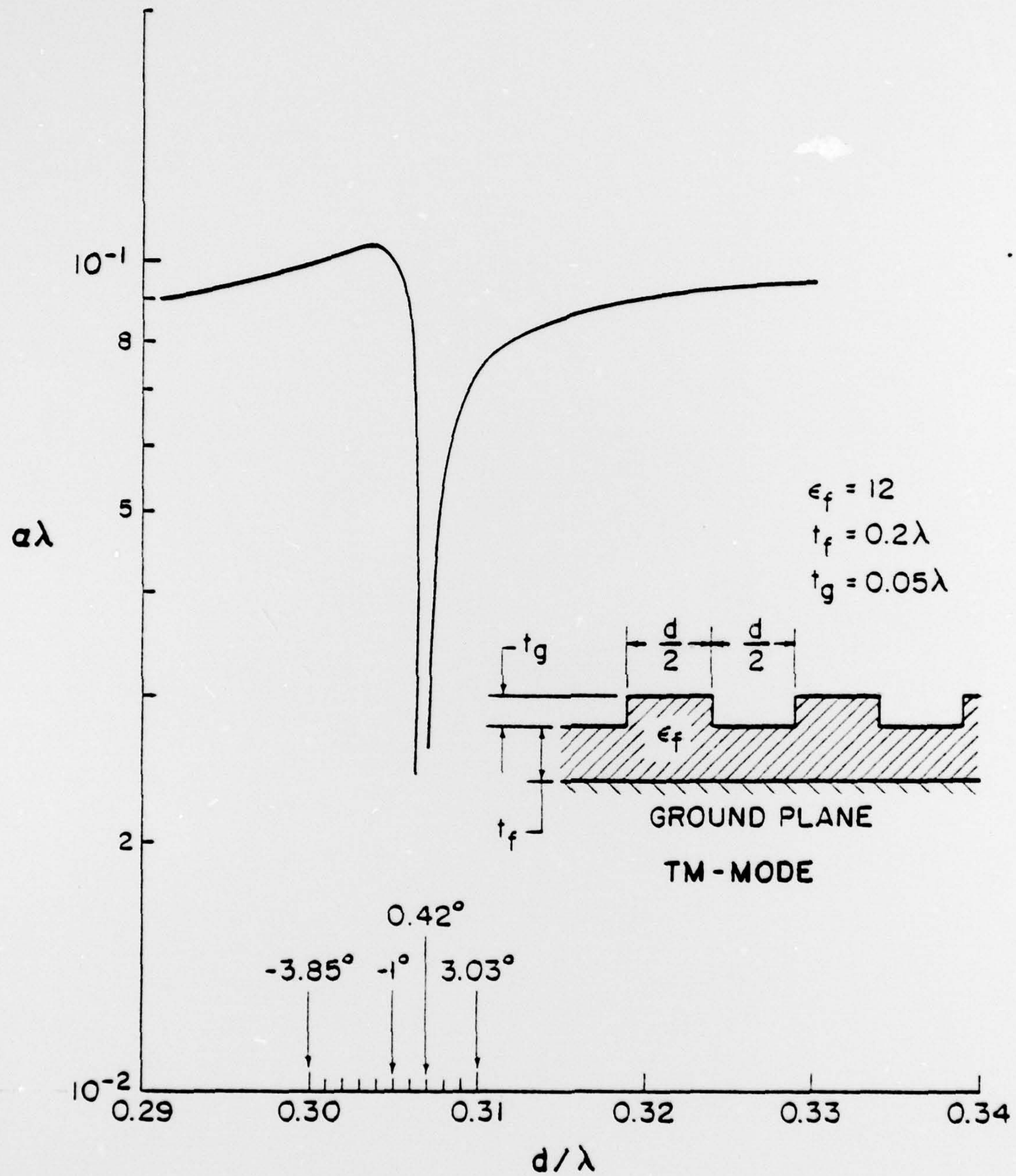

Fig. 4. Dispersion curve in the stopband region - leakage constant.

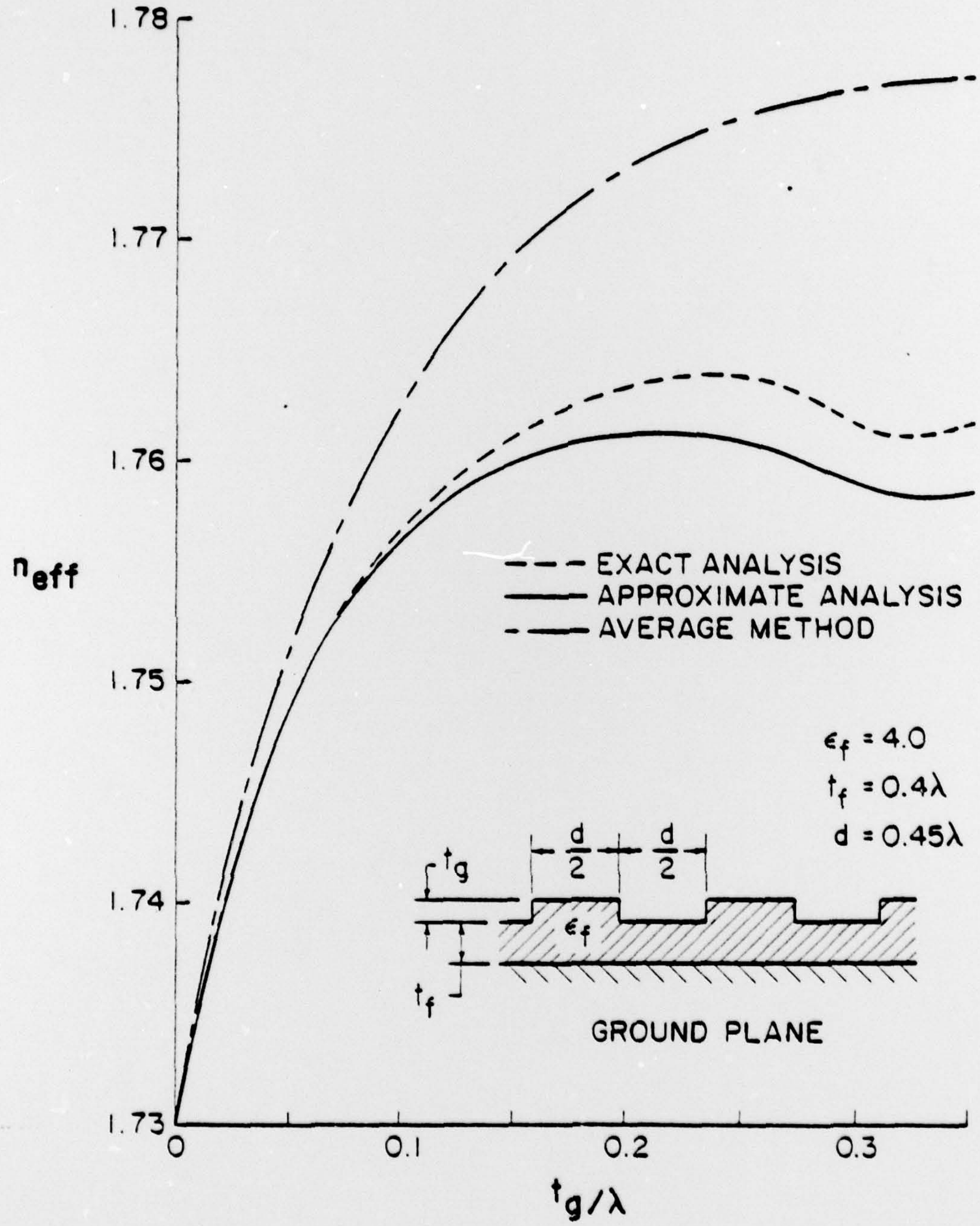

Fig. 5. Effective index of refraction vs. groove height.

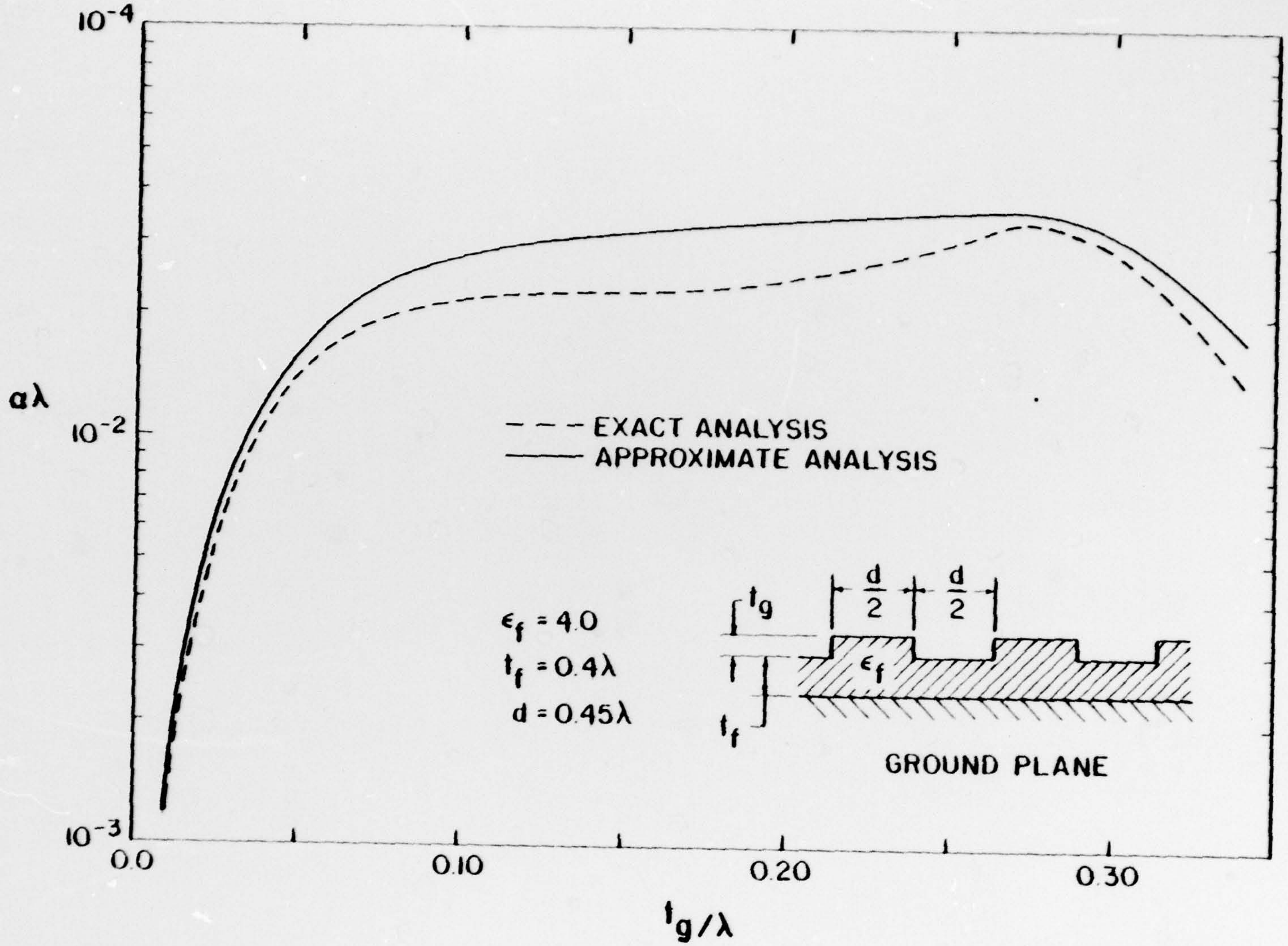

Fig. 6. Leakage constant vs. groove height.

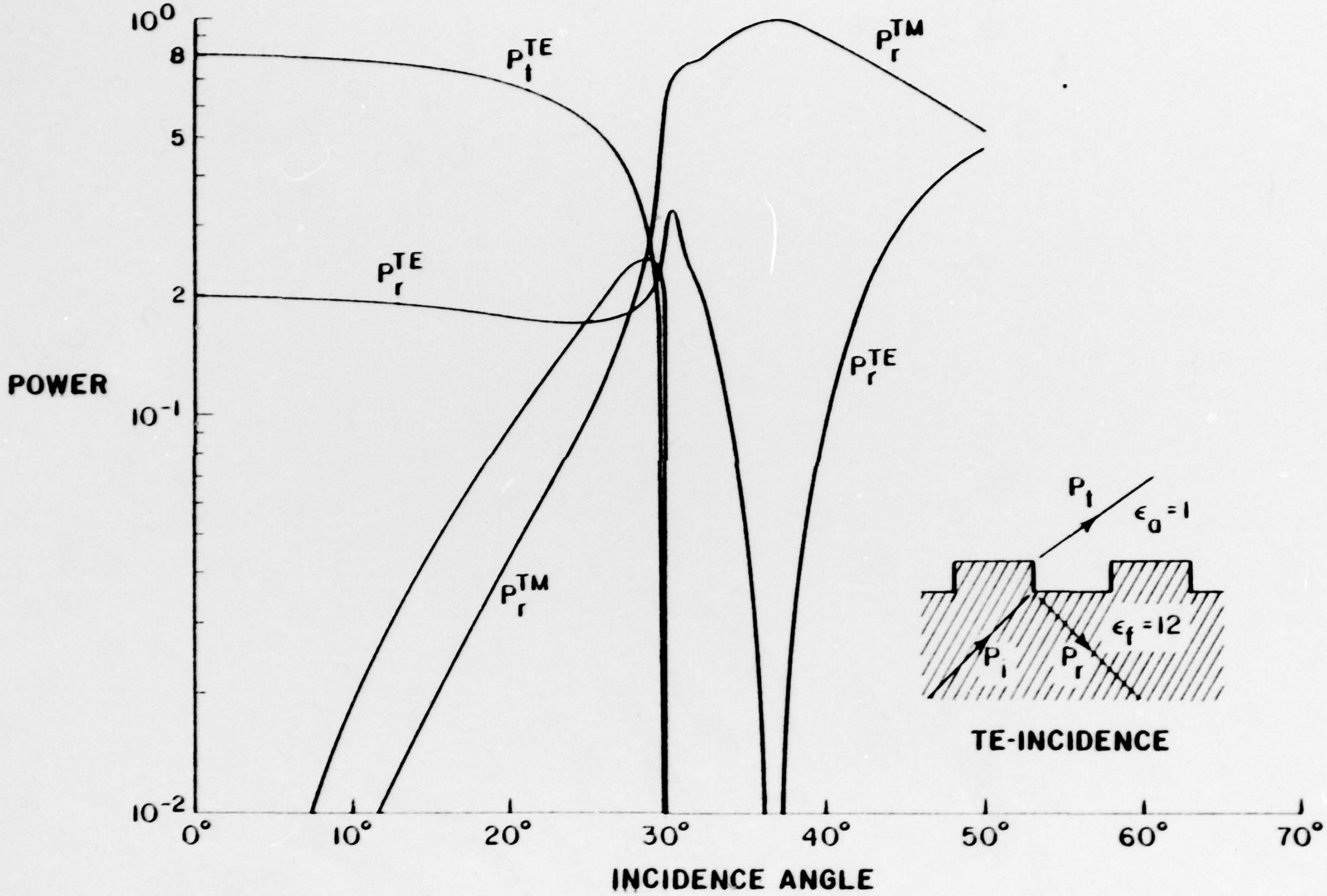

Fig. 7. Power coupling between TE and TM modes - TE incidence case.

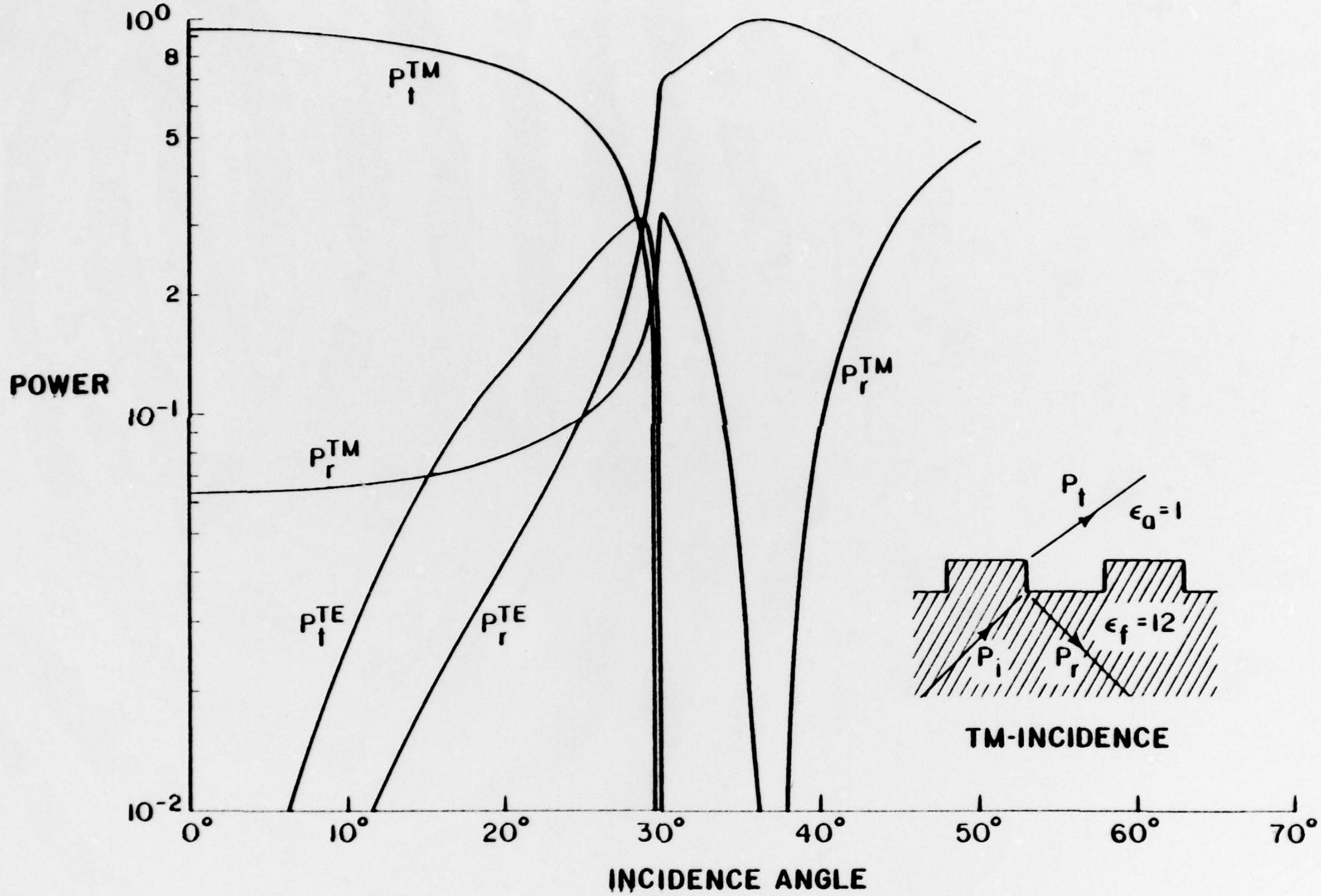

Fig. 8. Power coupling between TE and TM modes - TM incidence case.